TECHNICAL EXCELLENCE

Environmental Restoration

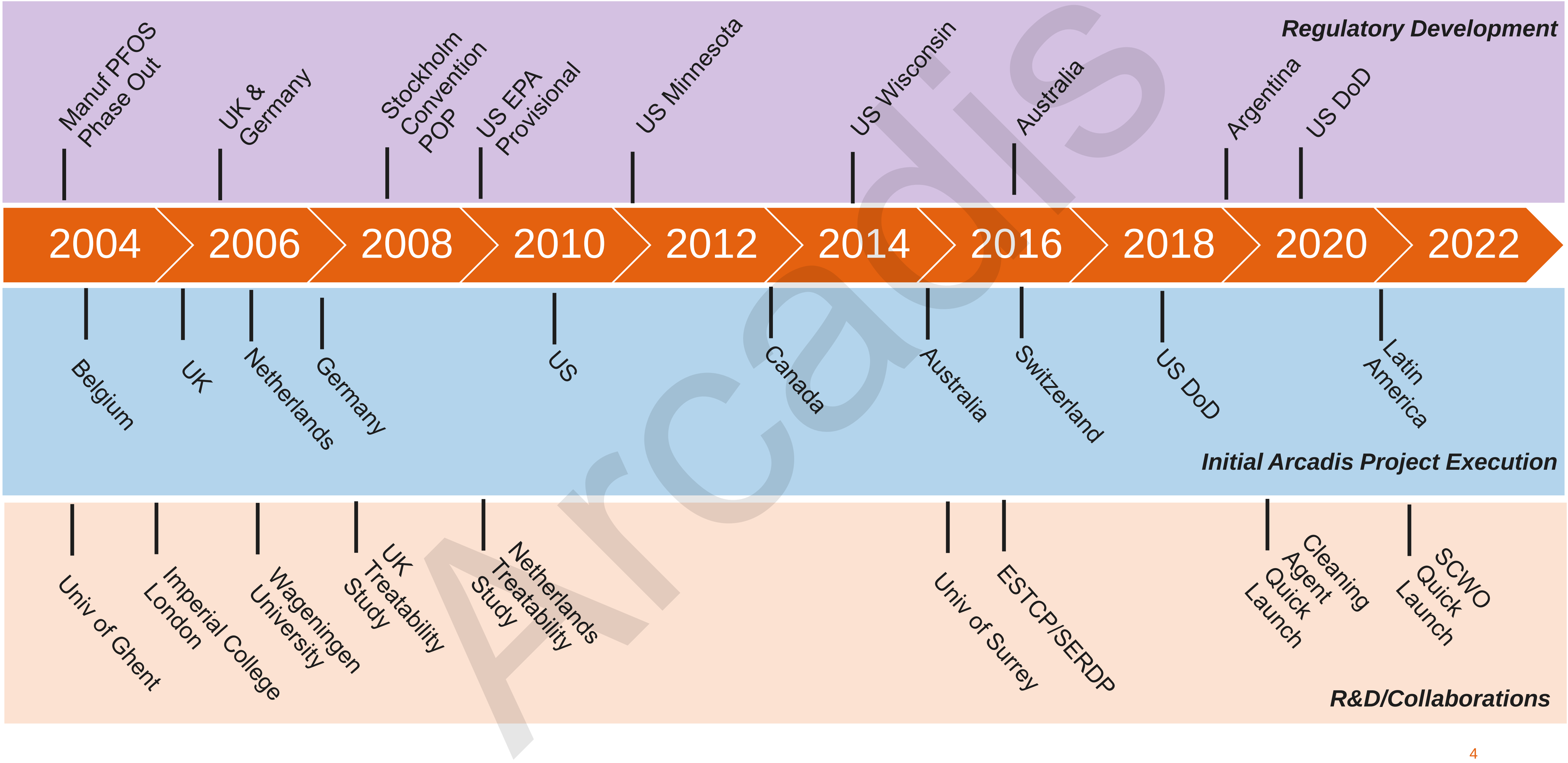
PFAS Remediation Options: Water and Soil Treatment

Jeff Burdick – Global Solutions Director
Antwerp, 18 April 2024

Agenda

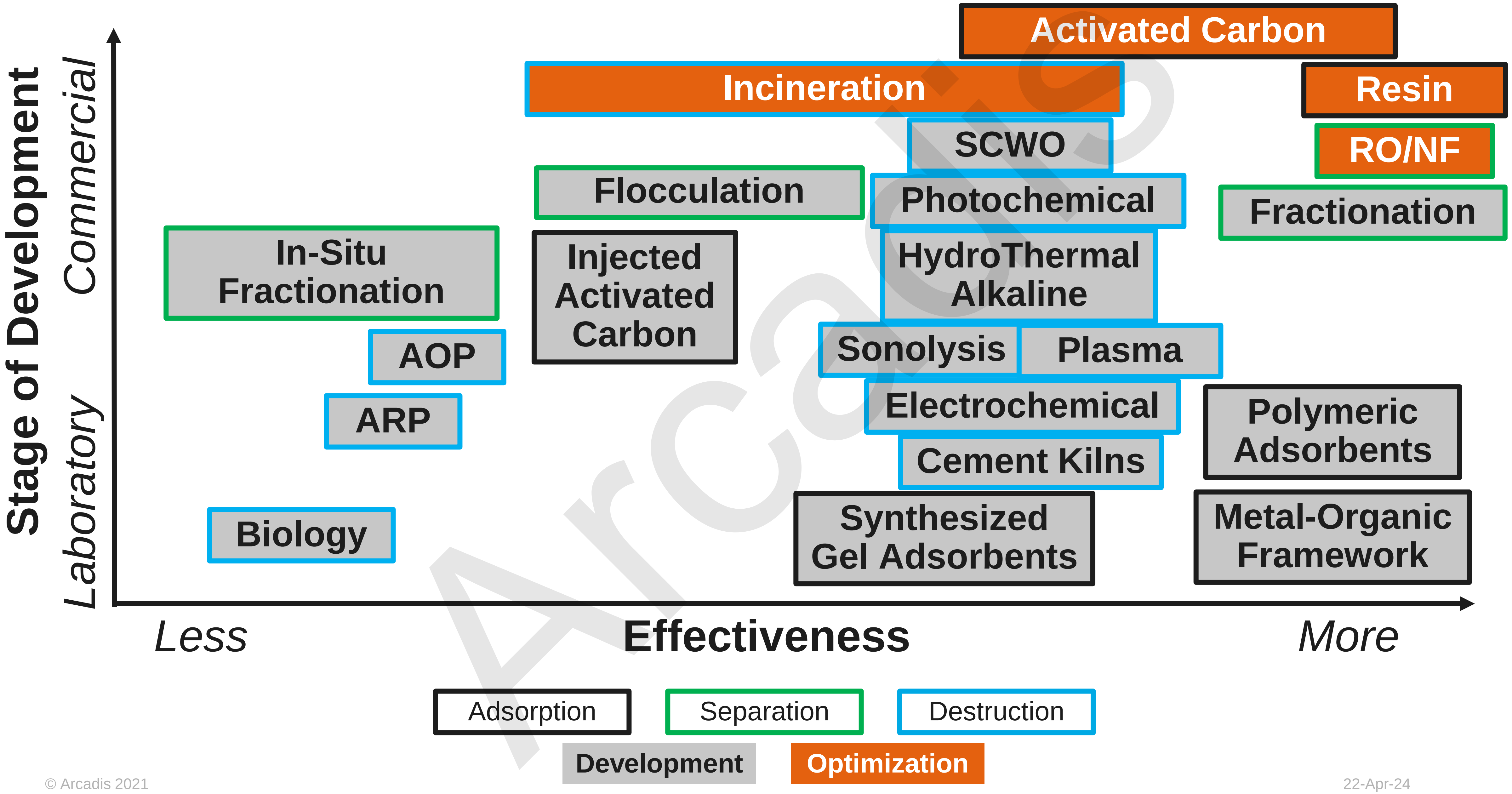
- Arcadis Timeline
- Groundwater/Drinking Water Treatment
- Soils Treatment
- Mythbusting: In Situ Carbon Injection

Arcadis and PFAS

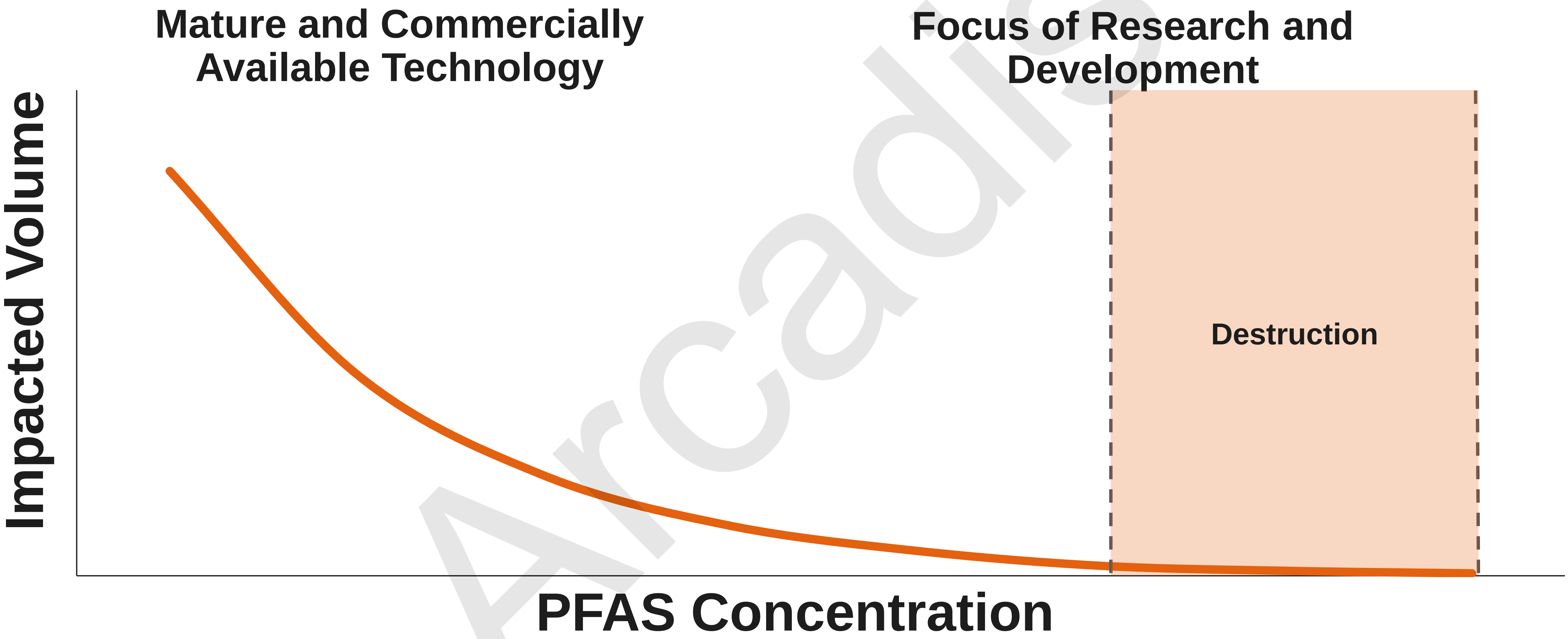


PFAS Water Treatment Technologies

PFAS Treatment Technologies for ***Liquid***



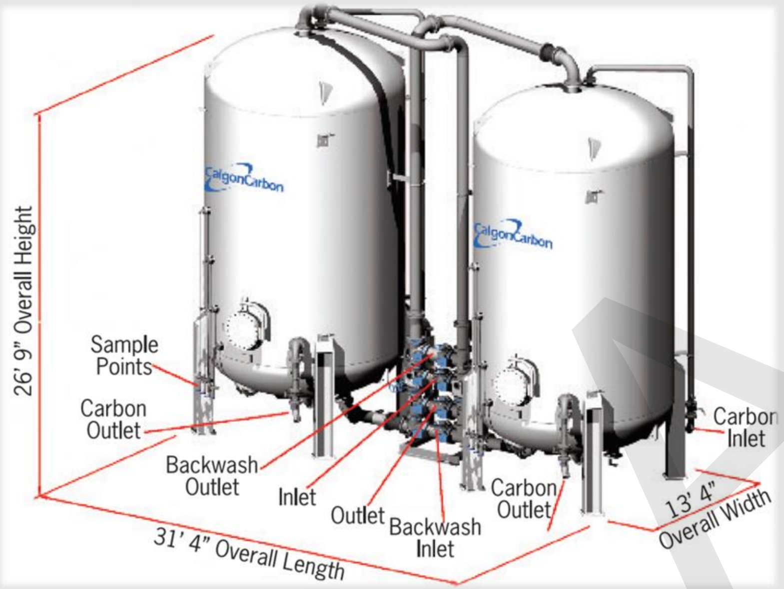
PFAS Treatment State of the Practice



Reduce impacted volume while concentrating PFAS for energy-intensive destruction.

Granular Activated Carbon

The industry standard



2-vessel GAC Skid: Model 12-40

Applicability

- Effectively removes PFOS/PFOA from water, >90%
- Best in Lower PFOS/PFOA concentrations with compatible geochemistry
- Bituminous often outperforms coconut and lignite
- Reactivated GAC can save ~15%

Limitations

- Competition with natural organics and other contaminants, higher pH to reduce this impact
- Effectiveness decreases as PFAA chain length decreases, but can be managed with longer EBCT

Providers

- Calgon Carbon / Kuraray
- Cabot / Norit
- Evoqua
- Puragen (new)
- Jacobi (EU, owned by Osaka Gas)

Optimizing Activated Carbon (Granular)

Understand the commercially available AC:

- Bituminous, sub-bituminous, anthracite, lignite, coconut shell
- Mesoporous GAC (e.g., coal, lignite) demonstrates better sorption capacity for PFASs than microporous GAC (e.g., coconut)
- GAC with lower density (e.g., sub-bituminous) may be more cost effective if it performs similarly to higher density GAC (e.g., bituminous) (**Table 1**)

Natural organic matter (NOM), measured as total organic carbon (TOC), is found in natural waters (<0.5 to >3 mg/L).

- TOC can outcompete PFOA/PFOS for adsorption site/pore obstruction (**Table 2**).
- TOC becomes less sorptive as pH increases; slight pH adjustments pre-AC may improve efficiency.

GAC Type	BV to Initial PFOA Breakthrough	BV to Initial PFOS Breakthrough
Bituminous	12,000	12,000
Sub-bituminous	12,000	19,000

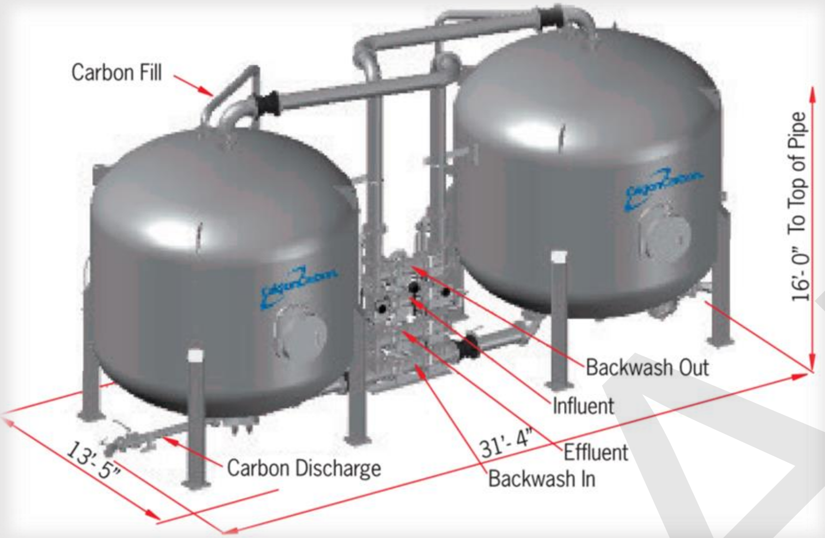
Table 1: Comparative PFOA/PFOS breakthrough at >3 mg/L TOC and ~150 ng/L PFOS and 25 ng/L PFOA influent concentrations

Influent PFOA Conc. (ng/L)	TOC (mg/L)	BV to Initial PFOA Breakthrough
20	0.3	>100,000
25	3.3	25,000

Table 2: Comparative influence of TOC on PFOA breakthrough

Resin

Ion Exchange and Adsorption



2-vessel Resin Skid: Model 12

Applicability

- Effectively removes PFOS/PFOA from water, >90%
- Engineered resins enable enhanced "selectivity"
- Lower EBCT than GAC (2 - 5 min) means smaller equipment footprint
- Regeneration possible, though single pass is often more economical

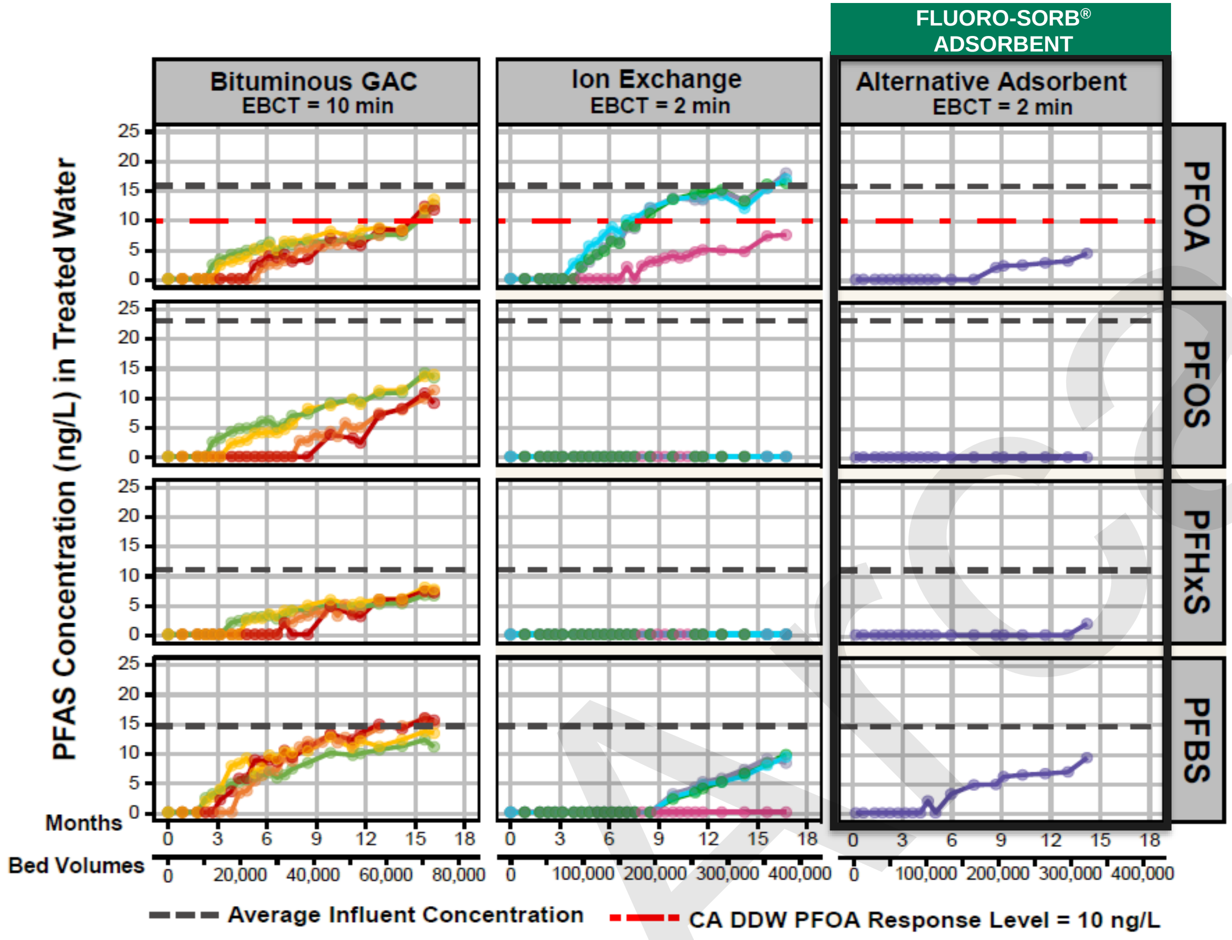
Limitations

- Can be higher CAPEX compared to GAC
- Media density may result in higher pumping costs
- Sensitive to site-specific geochemistry
- Complex/costly regeneration requires solvents or brine (or both)

Providers

- Purolite
- Lanxess
- Dow/Dupont

Orange County Water District Field Pilot Drinking Water Results



Results derived from study conducted by large public water district:

Effective across the broad range of PFAS molecules

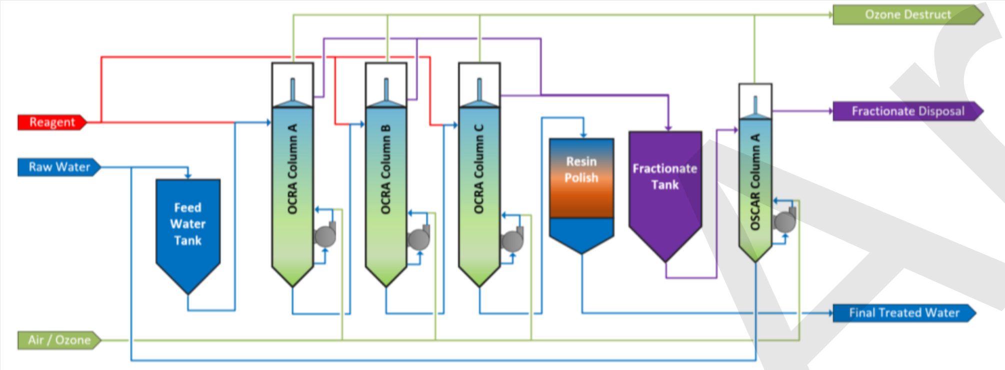
Less affected by organic carbon

Published Phase 1 Report : "FLUORO-SORB® 200 Adsorbent showed the latest initial breakthrough of all 14 medias tested with EBCT and footprint akin to Ion Exchange Resins."

Fractionation

Tiny Bubbles of Ozone or Air

- OCRA- Ozofractionative Catalyzed Reagent Addition
- OSCAR - OCRA Super Concentrating ARray



Applicability

- Gas sparging creates a PFAS foam concentrate
- Surfactant characteristic of PFAS favors accumulation at the gas-liquid interface
- Various gases may be used to mitigate co-contaminant impacts

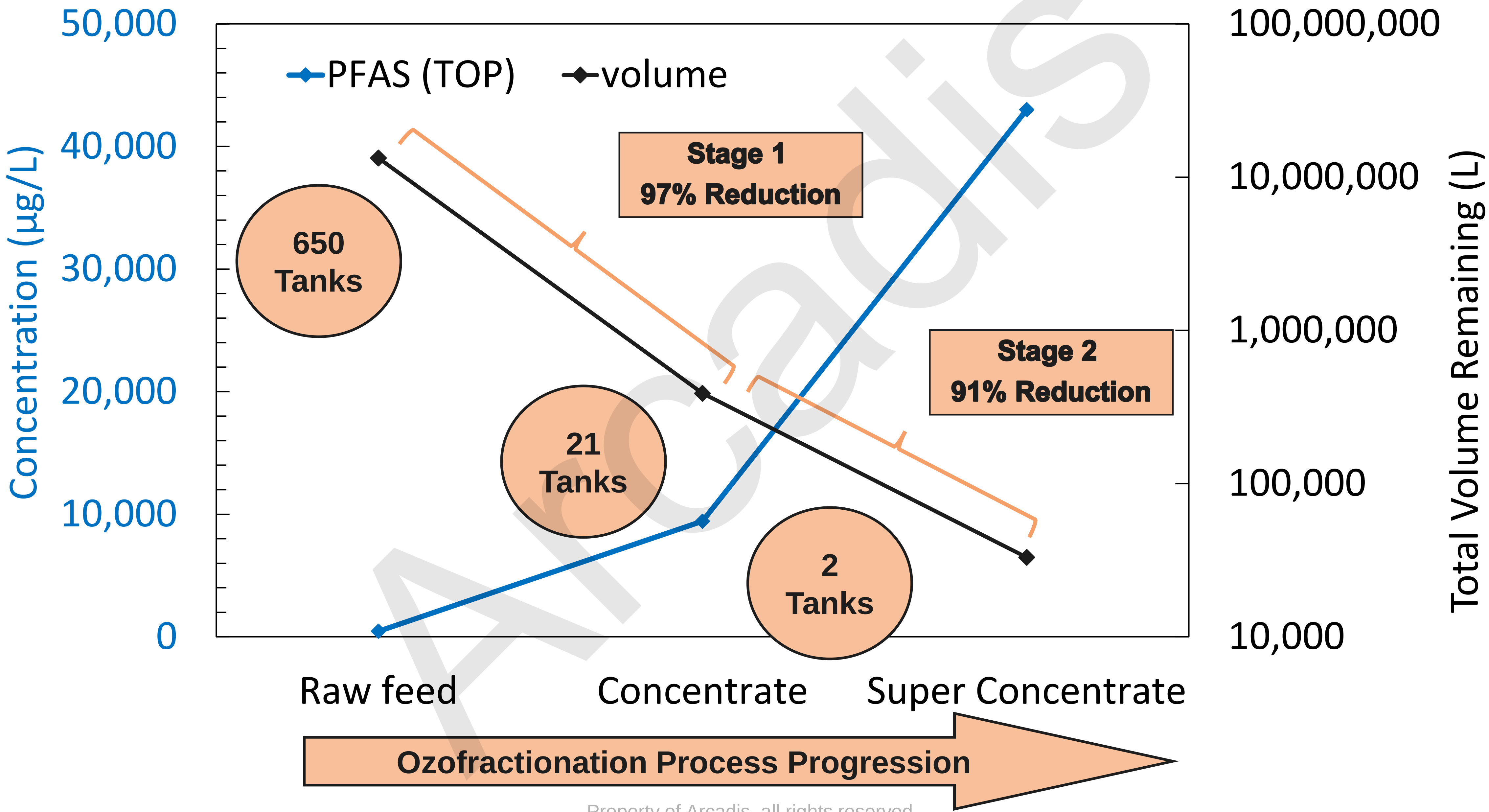
Limitations

- Site-specific contact time may not be cost effective for higher capacity systems
- Concentrated foam (0.5% to 2% of the treated water volume) requires treatment or destruction

Providers

- EVOCRA (negotiations are now complete)
- OPEC/EPOC - Allonia

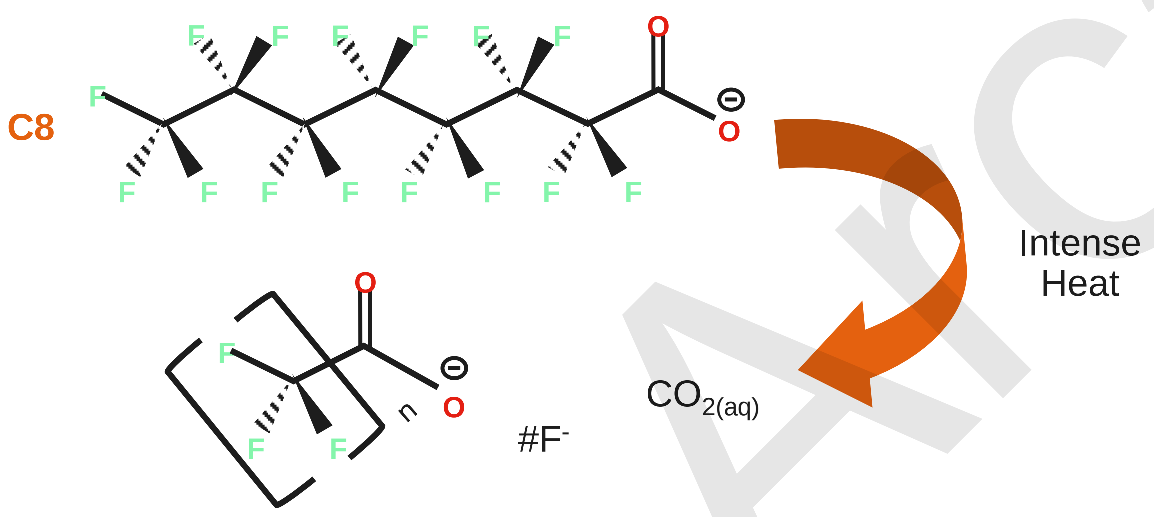
Australian Case Study: Waste reduction/Concentration



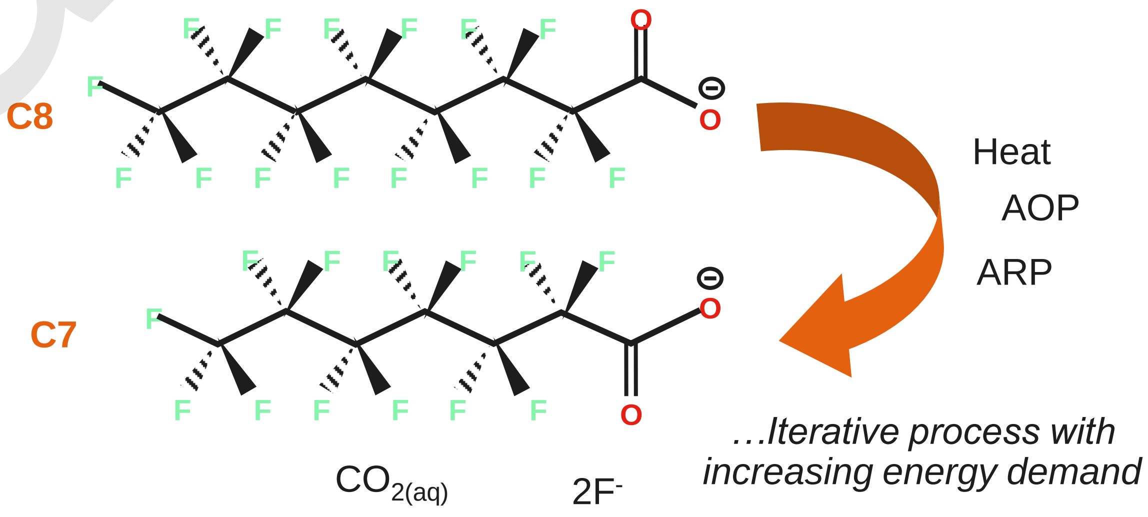
Destruction

Destruction of PFAS

- Mineralized species will not reform carbon fluorine bonds
- Defluorinated chain eventually oxidized to:
  - carbon dioxide (CO_2)
  - fluoride (F^-; hydrogen fluoride [HF])



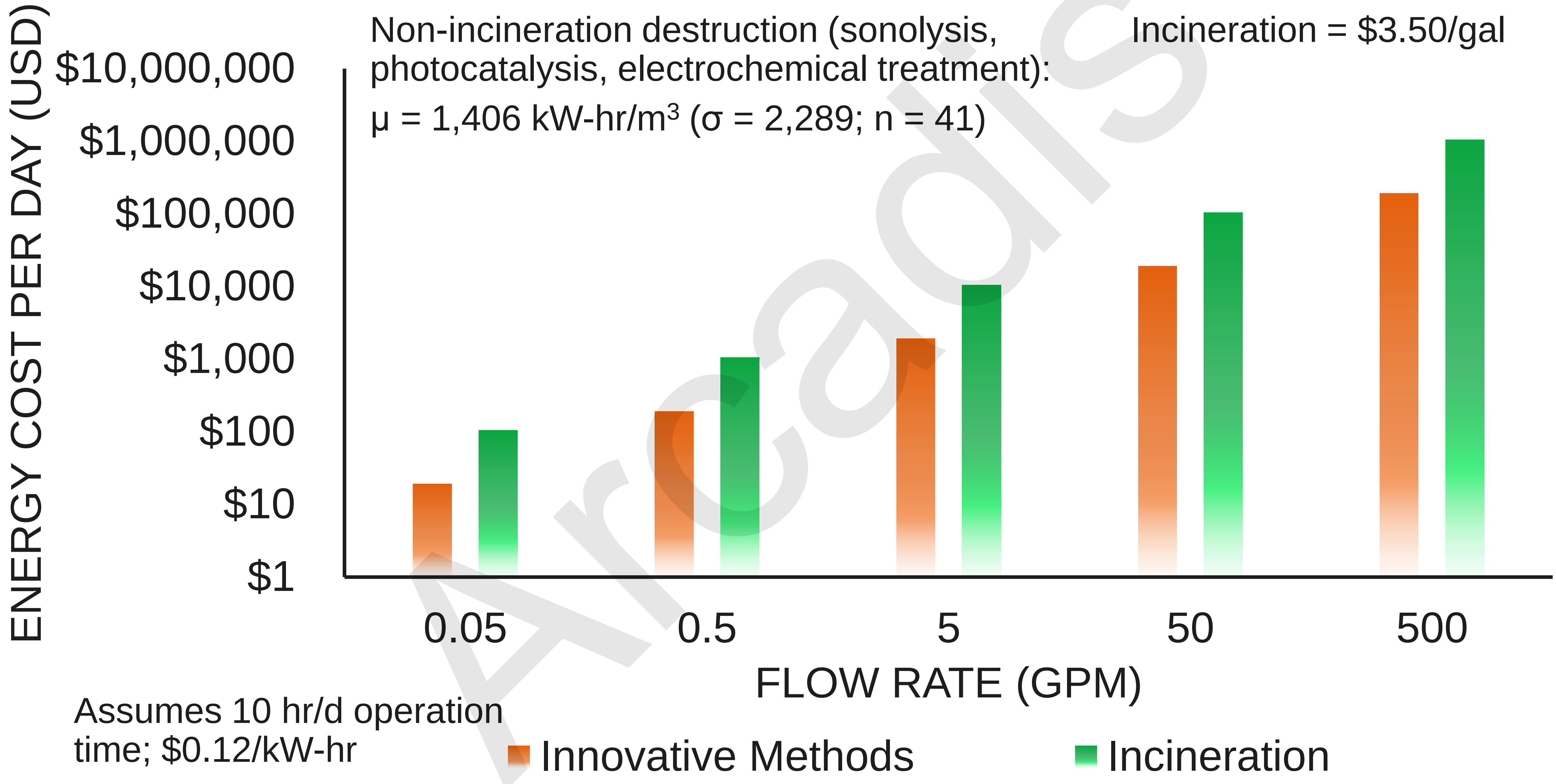
Mineralization



Defluorination

PFAS-Destruction Technologies Relevance

PFAS Destruction Energy Considerations (OPEX)



Destruction Technology Comparison

ARCADIS

Technology	Average DRE	Slurry Influent	High Salt Influent	Limitations	Throughput	Energy Requirements	Temp	Chemical Additives	Pretreatment Requirements	Byproducts	Cost
SCWO	High	Medium (vendor dependent)	Poor	Salt	High	High during startup, lowing during steady-state	High	Variable (oxidant source, effluent neutralization requirements)	Higher performance with concentrates	Metals leaching in some cases	High CapEx, low OpEx
HALT	High		Good	Chemical additive requirements	Medium-High	Medium-High	Medium-High	NaOH		Metals leaching in some cases	
Sonolysis	High	Good		Throughput	Medium	Medium-High	Low	None	None		
EO	Medium		Good	OM interference; short-chain	Low	Medium	Low	Salt (when ionic strength of feedstock is inadequate)	Higher performance with concentrates	$KClO_4$, ClO_3, bromine products	Boron-doped diamond (BDD) electrode cost = $7,125/m^2
Photochem	Medium		Medium-Good	nitrates	Low	Low	Low	Reagents up to 7.5% (possible to recycle reagents?)		short-chain PFAS	
Plasma	High	Good	Good	pH (acidic is better), OM, nitrates	Medium	1,500 – 2,500 kWh/m^3	Low (NTP) to Medium (TP)	None required (Argon can improve performance); effluent pH adjustment		ClO_3, ClO_2^-, short-chain PFAS	

DRE = destruction removal efficiency, **SCWO** = supercritical water oxidation, **HALT** = hydrothermal alkaline treatment, **EO** = electrochemical oxidation
Throughput may also be thought of as reaction or residence time, **NTP** = non-thermal plasma, **TP** = thermal plasma, **OM** = organic matter

Supercritical Water Oxidation (SCWO)

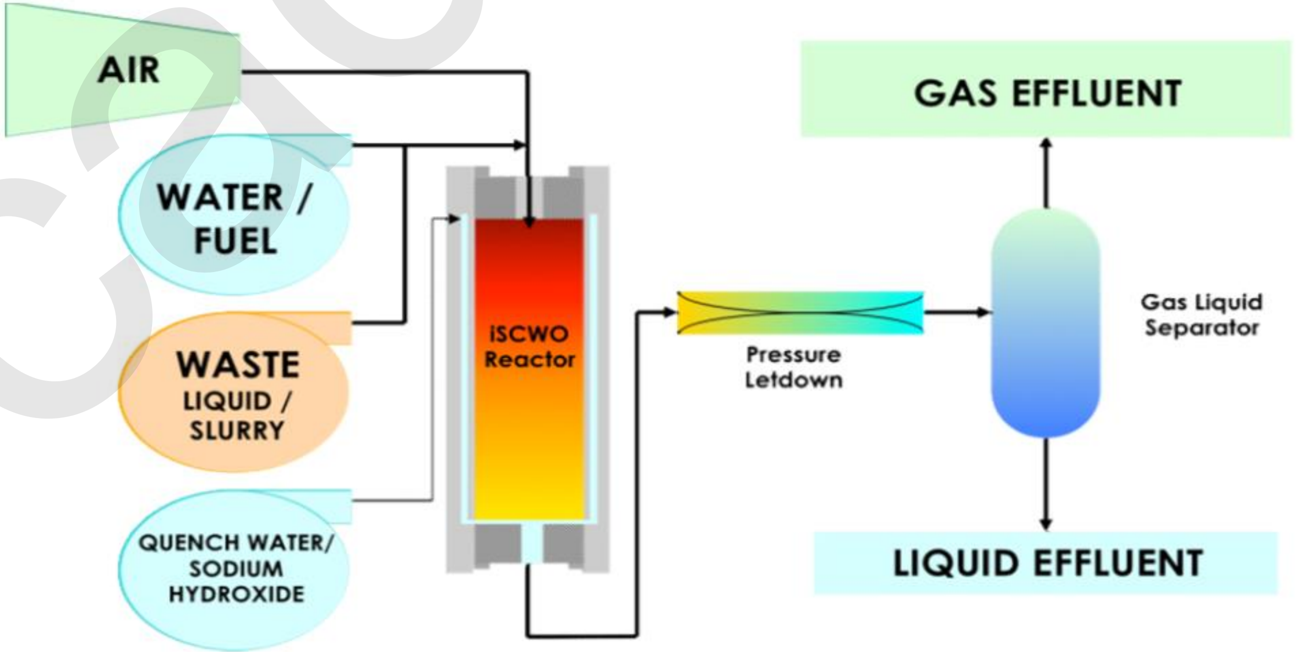
- Viability for PFAS destruction gaining consensus, particularly for concentrated streams
- Demonstrated effectiveness within the Department of Energy and Department of Defense
- Recent very successful demonstration completed with Arcadis and General Atomics using Quick Launch

https://otc.duke.edu/news/374water-converts-poo-to-water/

ARCADIS Design & Consultancy for natural and built assets

Validation of supercritical water oxidation to destroy perfluoroalkyl acids

https://doi.org/10.1002/rem.21711

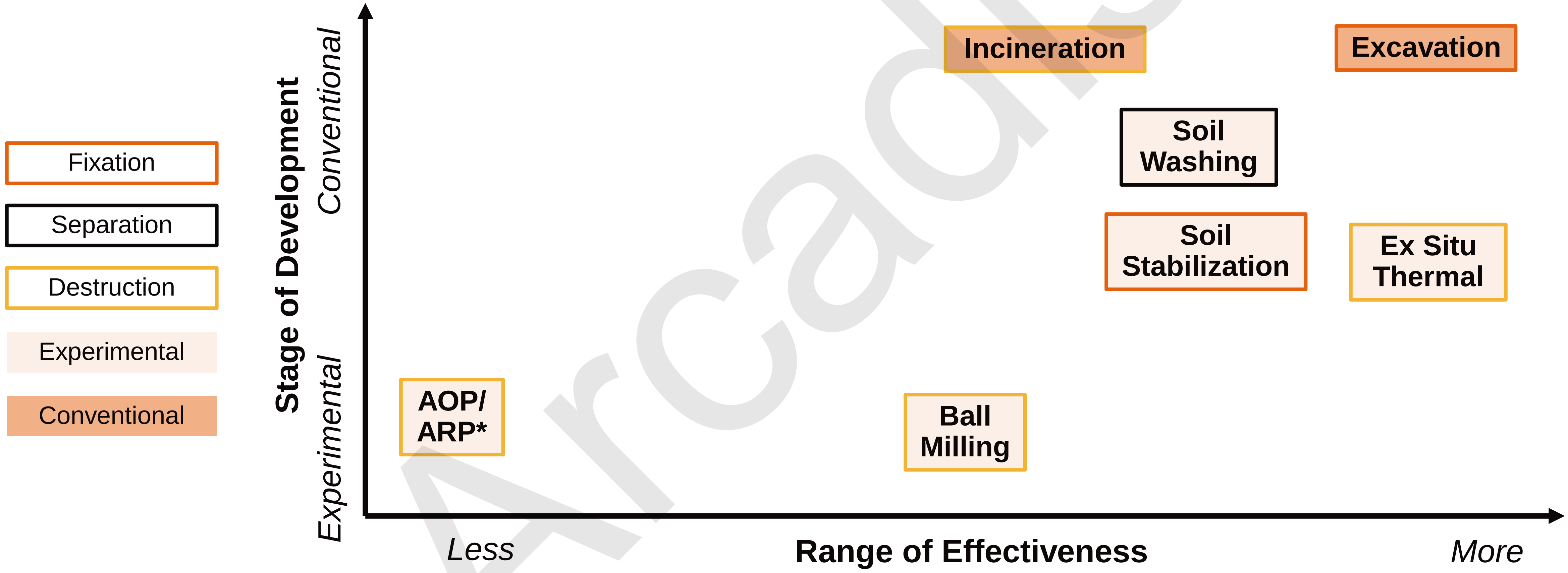


https://www.ga.com/hazardous-waste-destruction

Graphic and demonstration reproduced from General Atomics (with permission)

Soil Treatment Options

PFAS Treatment Technologies for Solids

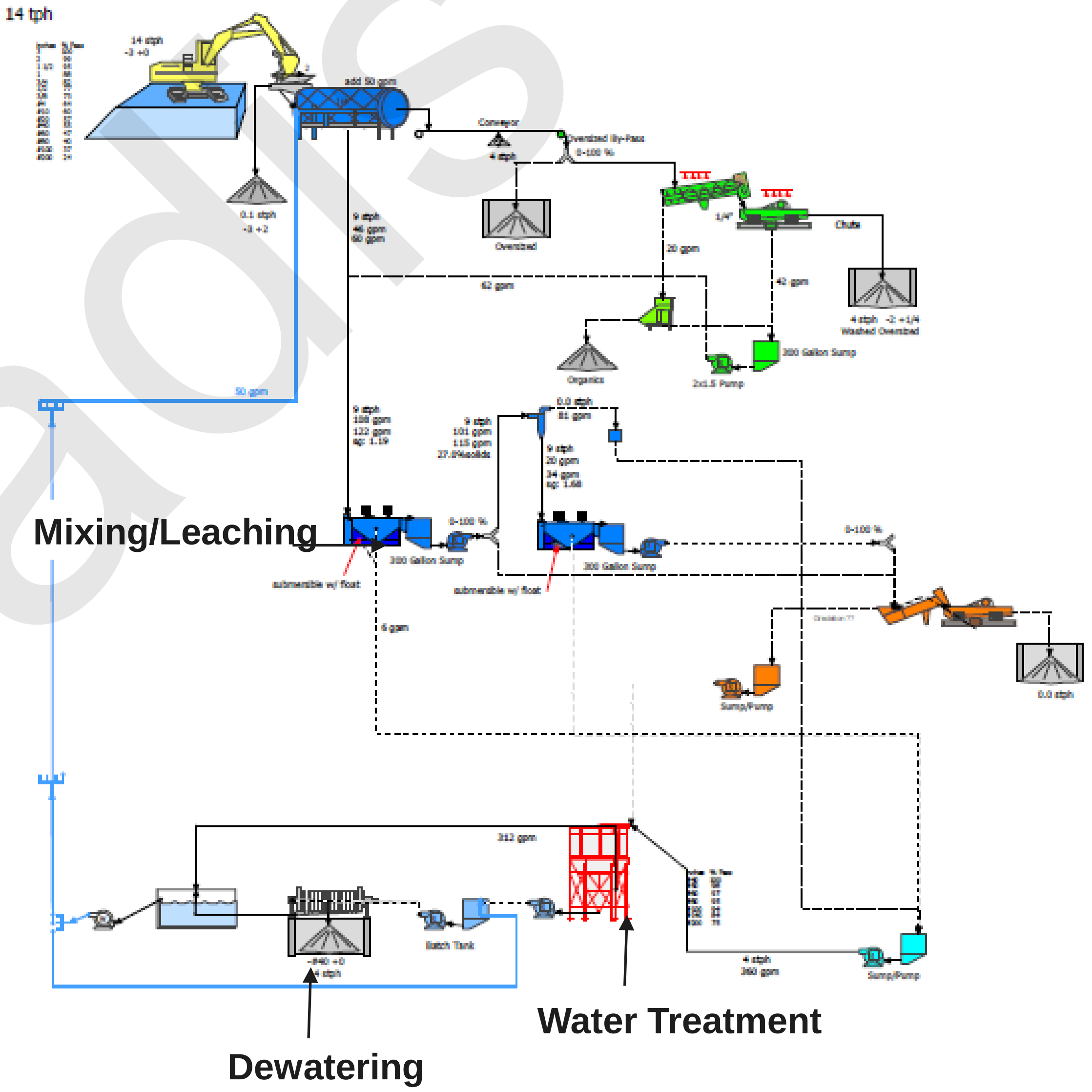


Soil Washing

Soil Washing Elements

- Physical and chemical treatment train
- Soil Preparation
- Physical Separation
- Size Separation
- Dewatering
- Wastewater Treatment
- Leaching

We optimize treatment of coarse fractions, and separate fines (silt, clay, organics) for alternative treatment and least total cost



ESTCP Results

Pile 393-1 is an AFFF source area

- Soil is mostly sand and gravel, about 20-30% fines
- ADEC standards are based on soil concentrations of PFOA, PFOS, PFBS
  - No leaching-based standard
- Goal is to be cost competitive with landfilling in the lower 48 states, as Alaska is very expensive
  - $500+ per ton to landfill in OR
  - $350+ ton to use thermal desorption
- Soil washing is a waste minimization strategy,
  - Soil washing for sand and gravel
  - Landfilling or thermal for fines
- Much less cost than thermal, competitive with landfilling

Material Type	PFBS	PFOA	PFOS	RE%
Untreated	**6.6 J**	11 U	**2700**	
Round 1				
Rock	0.5 U	0.5 U	**88**	**96.7%**
Gravel	0.5 U	0.5 U	**27**	**99.0%**
Sand	**0.26**	**0.55 J**	**150**	**94.4%**
Fines	**3.1 J**	7.5 U	**2400**	**11.1%**
Round 2				
Rock/Gravel	0.55 U	0.55 U	**8.8**	**99.7%**
Sand	0.47 U	0.47 U	**12**	**99.6%**
Iron	**1.6 J**	2.1 U	**190**	**93.0%**
Round 3				
Rock/Gravel/Sand	**0.60 U**	**0.60 U**	**0.34 J**	**99.99%**
Criteria	**1,900**	**1.7**	**3**	

J = Estimated result < LOQ and > DL
U = Not detected at or above the LOQ

Concentrations reported as µg/kg
RE% = PFOS Removal Efficiency

Cost Matrix for Lower 48

- Treating coarse soil with soil washing and separating fines for secondary treatment is cost effective for soil with up to 30% fines
- Soil washing soil with 10% fines saves up to 40% compared to landfilling
- Soil washing with thermal desorption is cost-effective up to 30% fines
- Soil washing can add value if sustainability or other metrics are important up to 50% fines

Scenario	Soil Composition					
	Fines	5%	10%	20%	30%	50%
	Coarse	95%	90%	80%	70%	50%
Low-Cost		**$110**	**$120**	**$140**	**$160**	$200
Medium-Cost		**$165**	**$180**	**$210**	**$240**	$300
High-Cost		**$215**	**$230**	**$260**	**$290**	$350

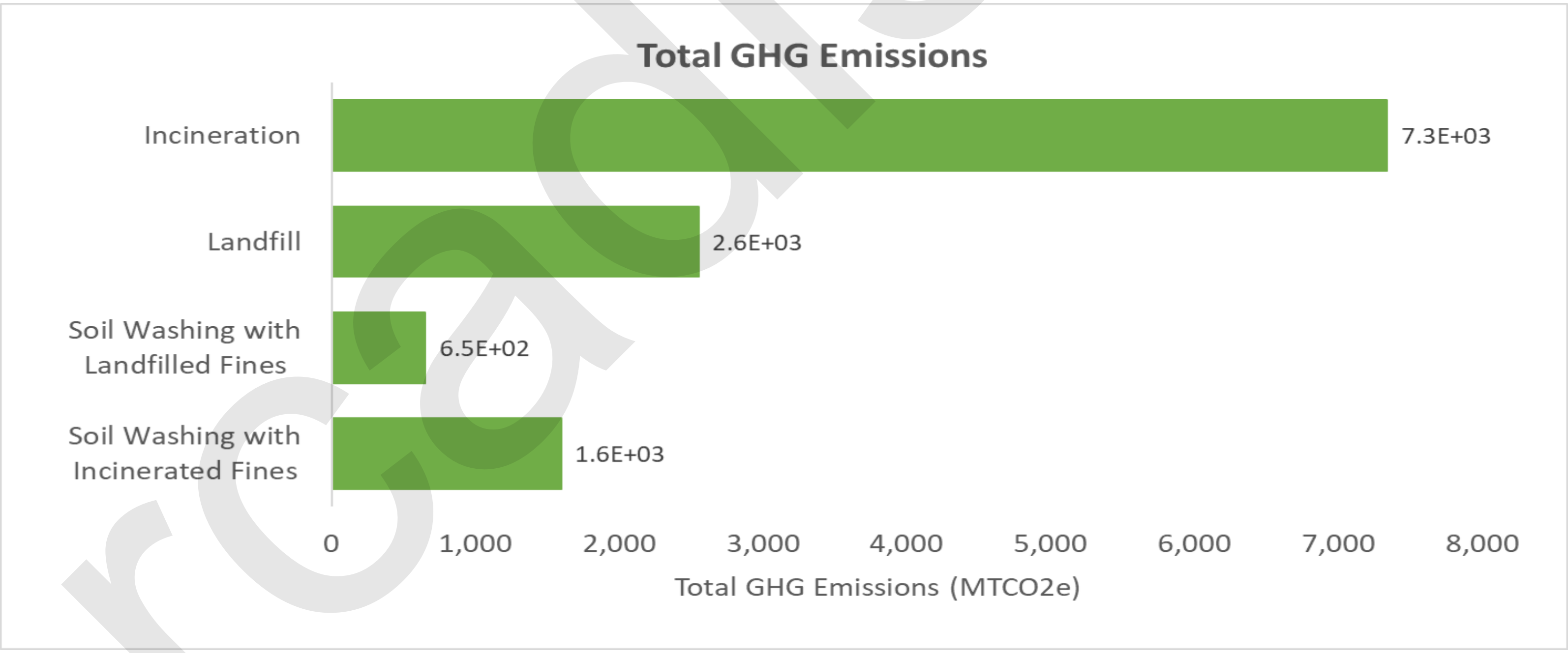
- **Bold** values are less than cost of landfilling at $200/ton (low-cost scenario) or thermal desorption at $300/ton (medium- and high-cost scenarios)
- **Low-Cost**: treatment of coarse soil using soil washing ($100/ton) and landfilling of fines ($200/ton)
- **Medium-Cost**: treatment of coarse soil using soil washing ($150/ton) and thermal desorption of fines ($300/ton)
- **High-Cost:** treatment of coarse soil using soil washing ($200/ton) and thermal desorption of fines ($300/ton)
- Assumes 25,000 tons of soil for economies of scale tipping the balance toward equipment mobilization vs transportation of soils to centralized disposal/treatment facility

Ongoing research to optimize fines treatment and minimize need for residuals treatment / disposal will improve sustainability and reduce costs

Sustainability Comparison

Soil washing 1.0 applied to 10,000 tons of soil

- 20% fines/organics either landfilled or incinerated
- Transport to incinerator or hazardous waste landfill – 1,000 miles
- Sand and gravel beneficially reused



Results

- Soil washing with landfilling - 25% of the total GHG for landfilling alone; 9% of total for incineration
- Soil washing with incineration - 61% the total GHG for landfilling alone; 22% of total for incineration

Soil Stabilization

Soil Stabilization

Soil stabilization consists of two primary mechanisms

- Chemical fixation to reduce leachability
- Permeability reduction to reduce infiltration though soils

Goal is to limit concentration and volume of leaching

- USEPA Dilution Attenuation Factor (DAF) approach
  - Mass balance between source mass loading and groundwater flow
  - Source loading: leachate concentration * infiltration rate * area of stabilized soil
  - Groundwater flow: area transverse to flow * hydraulic conductivity * hydraulic gradient

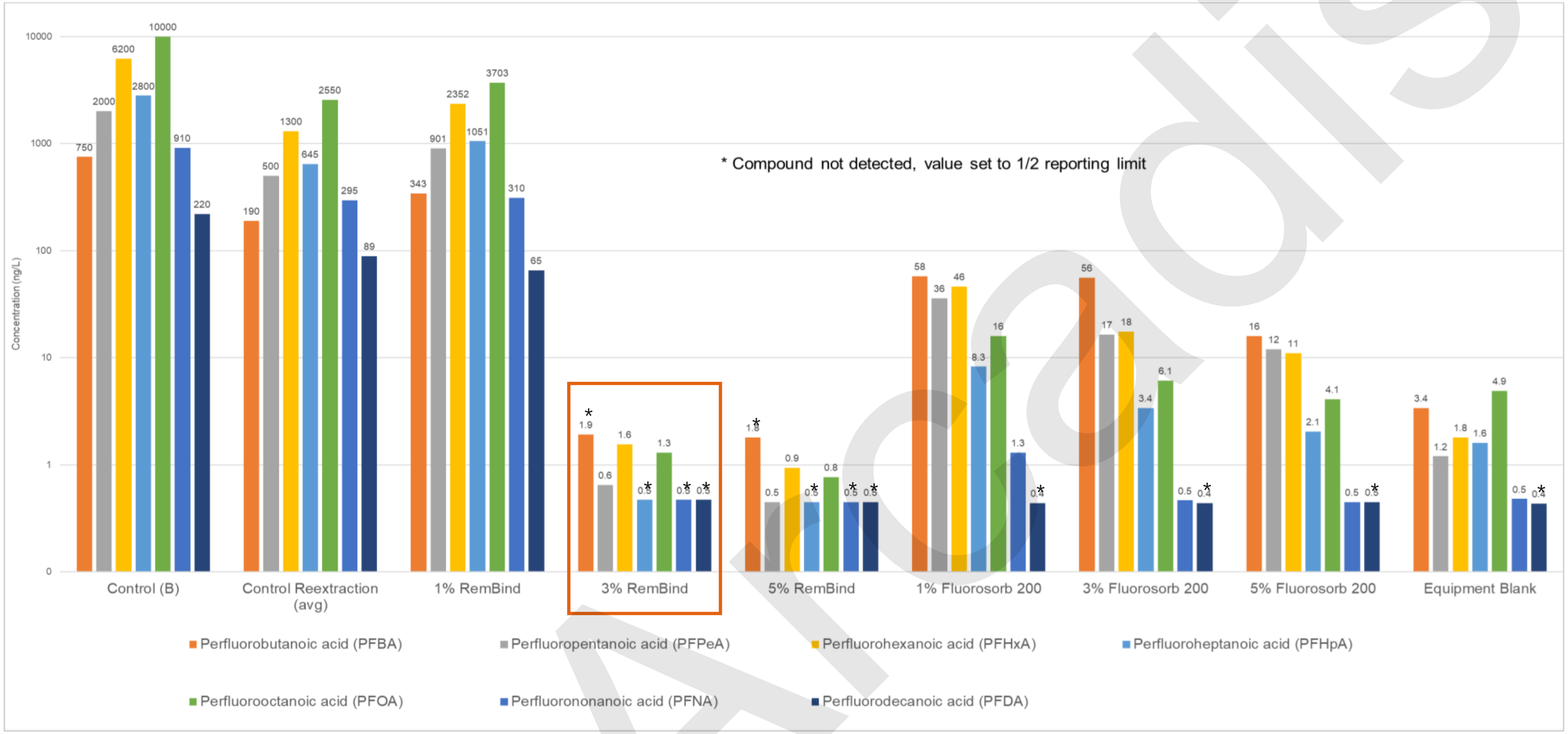
Can be used for pretreatment to meet landfill acceptance criteria

Synergy with soil washing for fines/organic fraction

Typical Approach

- Bench testing to optimize dose of fixant and cement for bearing capacity
- Field application – mix in place or pug mill
- Core testing – leachate and permeabilty
- Applied to entire source to meet GW RBSLs or partial source for mass flux reduction

Cavalier: Bench Treatability Results – PFCAs

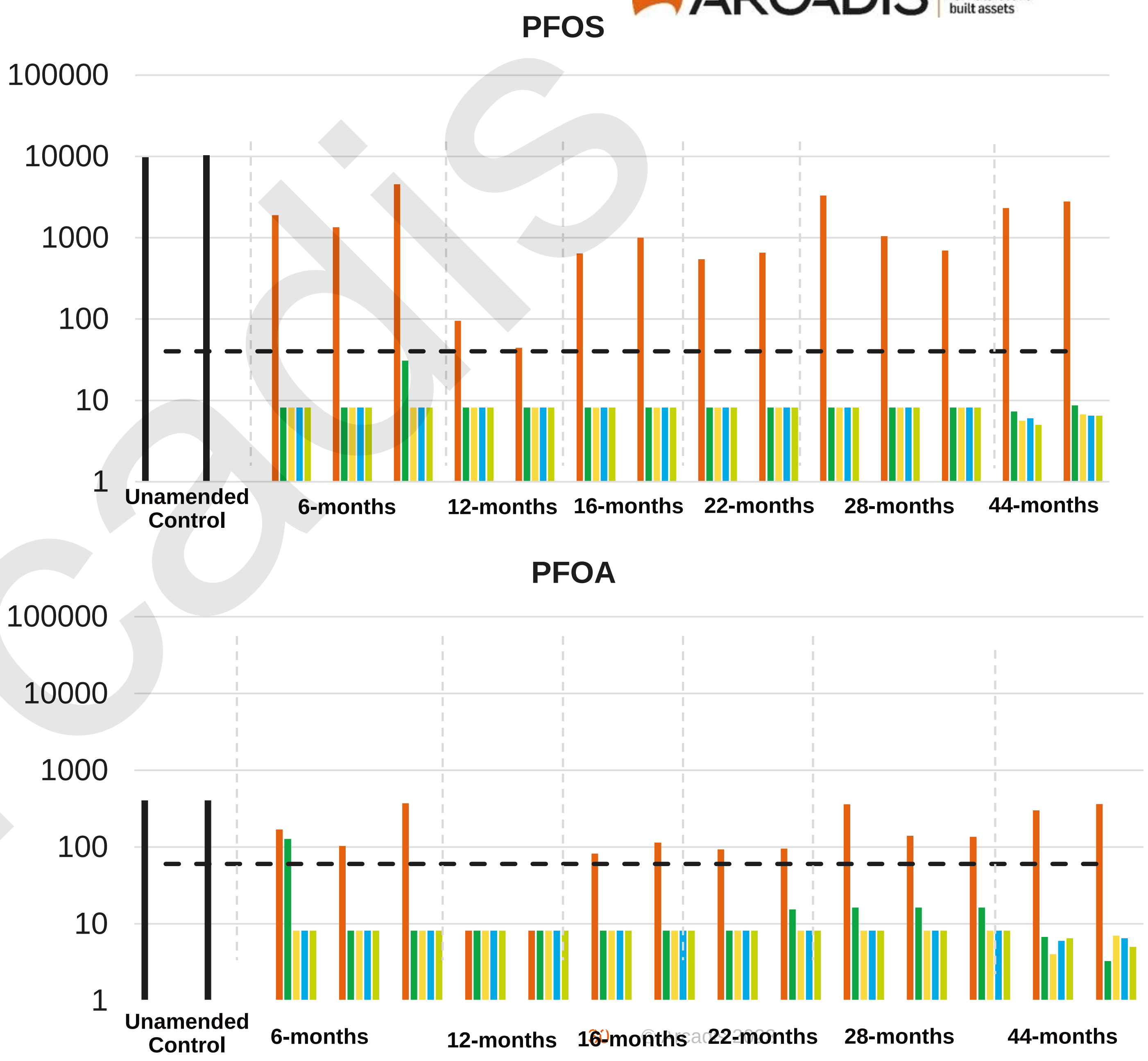


- 3 and 5% RemBind had highest levels of reduction for all PFCAs
- 3 and 5% Fluorosorb also reduced PFCAs, but performed worse for all PFCAs
- Fluorosorb had low reduction for shorter chain PFCAs compared to RemBind

ARCADIS Design & Consultancy for natural and built assets

Extended Field Data

- Compared several fixants at bench
- Selected best fixants and performed extended field evaluation of leaching using cores and LEAF 1314
- Cores used 5% Portland cement to prevent turtles from burrowing, normally applied for bearing capacity
- Leaching reduced 99.9% for PFOS and 98% for PFOA



Unamended Control

5% Portland Cement

5% FluoroSorb® and 5% Portland Cement

10% FluoroSorb® and 5% Portland Cement

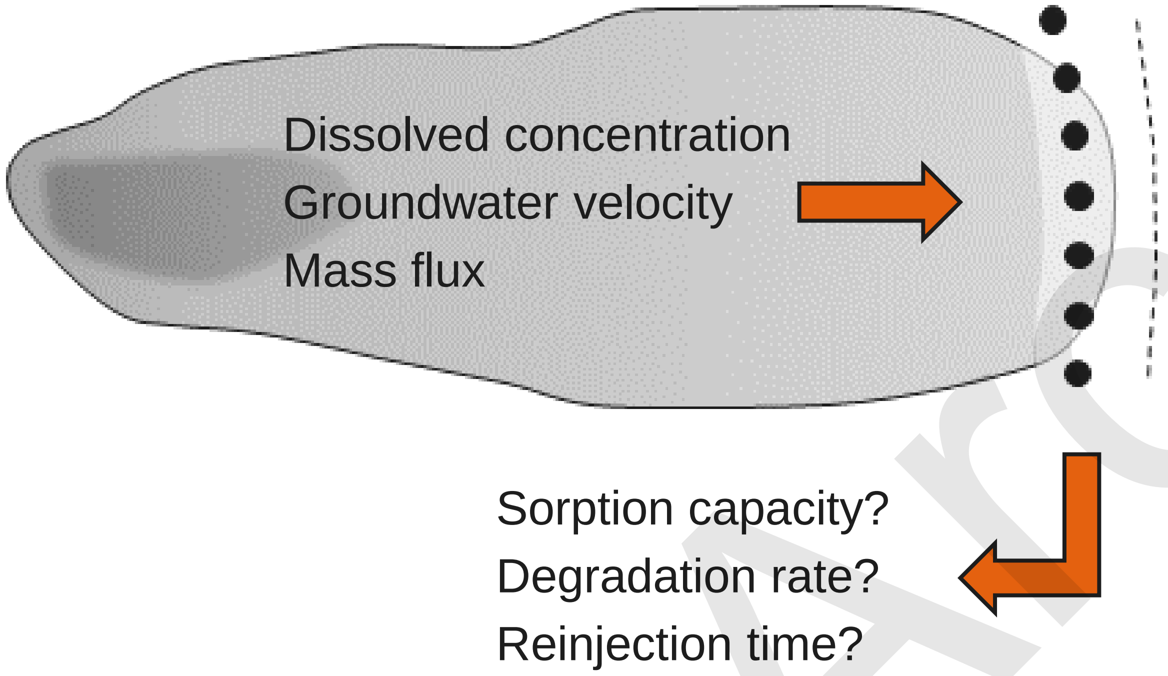
5% RemBind® and 10% Portland Cement

10% RemBind® and 10% Portland Cement

OSD Screening Level

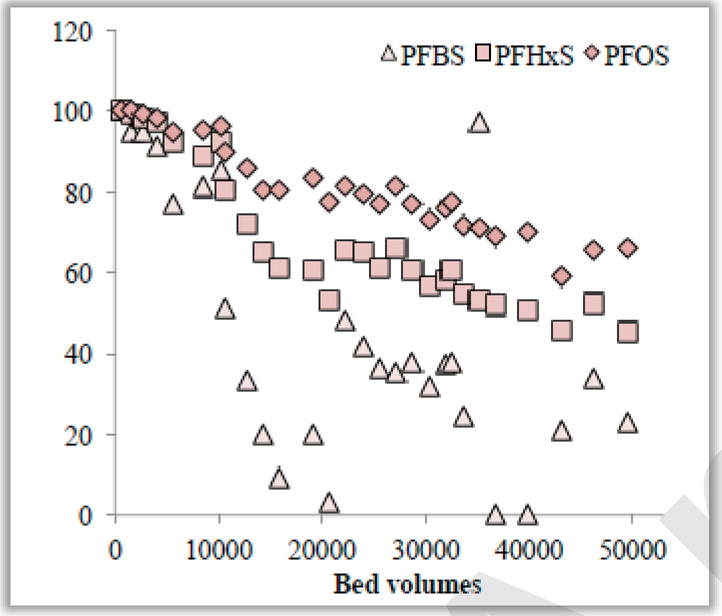
In Situ Sorption Reagent Application to PFAS

In Situ Sorption Reagents - Key Questions



- Are we just making a secondary concentrated source – is that relevant to objectives?
- How long to breakthrough and lost sorption capacity?
- Can it be injected uniformly?
- Is reinjection of additional GAC (which doesn't degrade) feasible?
  - Reductions in injectability?
  - Reductions in permeability?
- PFAS Sorption Remedy Challenges?

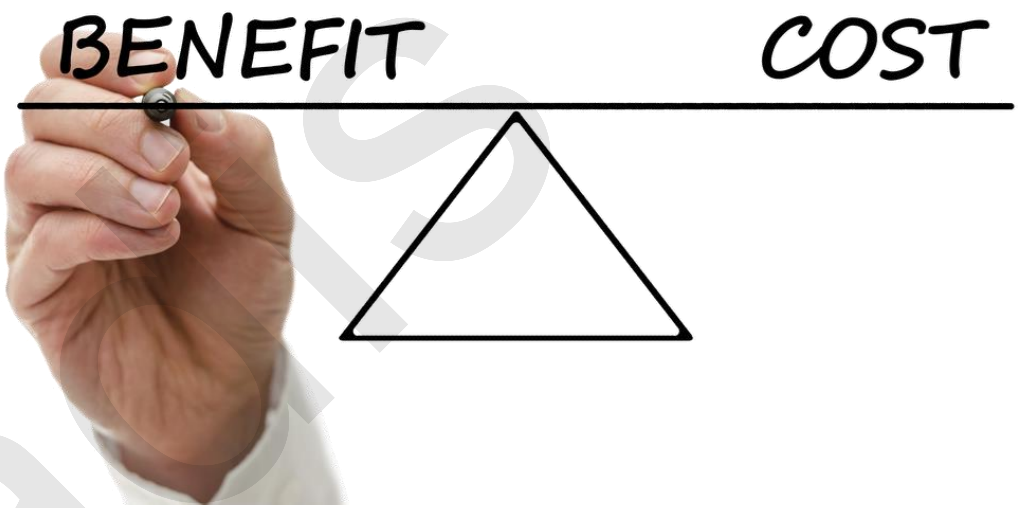
PFAS-Specific Sorption Realities



- Removal efficiency of select PFAS compounds with GAC
- *K. Lindegran (Dec 2015)*

- PFAS less sorptive than e.g. hydrocarbons (more rapid breakthrough)
- Co-contaminants (e.g. hydrocarbons) compete/displace PFAS compounds (reduces GAC efficiency)
- Do not biodegrade – no "indefinite sorption"
- Preferentially sorptive
  - More effective for Long-chained alkyl substances (e.g. PFOS, PFOA) compared to short chained alkyl substances
  - Some precursors are less sorptive than e.g. longer chained Perfluorinated Alkyl substances – Missing some of the hidden mass.
- Catch and release for current targets, less (or not) effective for broader suite of short-chained future targets and precursors
- Likely need to reinject GAC to sustain long term capture

In Situ Sorption Reagents & PFAS - takeaways



- Material pricing:
  - BOS200: $5.00 / lb
  - PlumeStop: $3 – 7 / lb

  May be on the order of $1M to $2.6M / acre covered
- Potential as temporary solution in the right geology – e.g. high mass flux zone(s) barrier approach.
- For long term effectiveness reinjection is likely required.
- Limited effect on short chain compounds under increasing regulatory scrutiny. Co-contaminant challenge to effectiveness (e.g. hydrocarbons).
- In-situ regeneration of injected carbon (i.e. destruction of PFAS) not currently achievable.
- Demonstrated limitations to distribution and achievable ROI

Injected carbon has its place in the PFAS toolbox – but likely best as an "interim solution"

Arcadis.
Improving quality of life.